neurophysin may hinder its further packaging and processing in the neurosecretory granules. On the other hand, the modified C-terminus may have caused the neurophysin to have lost one of its supposed functions, namely to protect the hormone from proteolytic degradation[20].

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1. Valtin, H., Stewart, J. & Sokol, H. W. *Handbk Physiol.* **7,** 131–171 (1974).
2. Pickering, B. T. & North, W. G. *Ann. N. Y. Acad. Sci.* **394,** 72–81 (1982).
3. Cheng, S. W. T., North, W. G. & Gellai, M. *Ann. N. Y. Acad.* **394,** 437–480 (1982).
4. Brownstein, J. M., Russell, J. T. & Gainer, H. *Science* **207,** 373–378 (1980).
5. Gainer, H. *Prog. Brain Res.* **60,** 205–215 (1982).
6. Land, H., Schütz, G., Schmale, H. & Richter, D. *Nature* **295,** 299–303 (1982).
7. Schmale, H., Heinsohn, S. & Richter, D. *EMBO J.* **2,** 763–767 (1983).
8. Sokol, H. W. & Valtin, H. *Ann. N. Y. Acad. Sci.* **394,** 1–828 (1982).
9. Valtin, H., North, W. G., LaRochelle, F. T., Sokol, H. W. & Morris, J. *Proc. 7th int. Congr. Nephrol.*, Basel, 313–320 (Karger, Basel, 1978).
10. Land, H. *et al. Nature* **302,** 342–344 (1983).
11. Ivell, R. & Richter, D. *Proc. natn. Acad. Sci. U.S.A.* (in the press).
12. Valtin, H. & Schroeder, H. A. *Am. J. Physiol.* **206,** 425–430 (1964).
13. Southern, E. M. *J. molec. Biol.* **98,** 503–517 (1975).
14. Maxam, A. M. & Gilbert, W. *Meth. Enzym.* **65,** 499–560 (1980).
15. Wallace, R. B. *et al. Nucleic Acids Res.* **6,** 3543–3557 (1979).
16. Breslow, E. *A. Rev. Biochem.* **48,** 251–274 (1979).
17. Lu, C.-L., Cantin, M., Seidah, N. G. & Chrétien, M. *J. Histochem. Cytochem.* **30,** 999–1003 (1982).
18. Martin, R. & Voigt, K. H. *Nature* **289,** 502–504 (1981).
19. Russell, J. T., Brownstein, M. J. & Gainer, H. *Endocrinology* **107,** 1880–1981 (1980).
20. Chirgwin, J. M., Przybyla, A. E., MacDonald, R. J. & Rutter, W. J. *Biochemistry* **18,** 5294–5299 (1979).
21. Blin, N. & Stafford, D. W. *Nucleic Acids Res.* **3,** 2303–2308 (1976).
22. Murray, N. E., Brammar, W. J. & Murray, K. *Molec. gen. Genet.* **150,** 53–61 (1977).
23. Breathnach, R. & Chambon, P. *A. Rev. Biochem.* **50,** 349–383 (1981).
24. Gal, A., Nahon, J.-L. & Sala-Trepat, J. M. *Analyt. Biochem.* **132,** 190–194 (1983).
25. Kidd, V. J., Wallace, R. B., Itakura, K. & Woo, S.L.C. *Nature* **304,** 230–234 (1983).

LETTERS TO NATURE

Terrestrial mass extinctions, cometary impacts and the Sun's motion perpendicular to the galactic plane

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Episodes of mass extinctions on the Earth are now strongly suspected to be cyclical[1]. We report here that our analysis of the data of Raup and Sepkoski[1] suggests that the dominant cyclicity in major marine mass extinctions during at least the past 250 Myr is 30 ± 1 Myr, with the standard deviation of an individual episode being ±9 Myr. We find this terrestrial cycle to be strongly correlated with the time needed for the Solar System to oscillate vertically about the plane of the Galaxy, which is 33 ± 3 Myr according to the best current astronomical evidence. It is argued that galactic triggering or forcing of terrestrial biological crises may arise as a result of collisions (or close encounters) of the Solar System with intermediate-sized to large-sized interstellar clouds of gas and dust, which are sufficiently concentrated towards the galactic plane to produce the observed cyclicity and its scatter. Among other consequences, a nearby interstellar cloud would gravitationally perturb the Solar System's family of comets and thereby increase the flux of comets and comet-derived bodies near the Earth, leading to large-body impacts. We find a dominant cyclicity of 31 ± 1 Myr in the observed age distribution of impact craters on Earth, the phase of this cycle agreeing with that shown by the major biological crises. Our galactic hypothesis can thus simultaneously account for the mean interval between major terrestrial crises and for the 50% scatter of the time intervals about their mean value.

Raup and Sepkoski[1] have very recently presented evidence for an approximate cyclicity in marine mass extinctions over the past 250 Myr. Fourier analysis of their data showed a dominant periodicity of 30 Myr, a best-fit curve yielded a cycle of 26 Myr, and a non-parametric test (previously developed independently and somewhat differently in ref. 2) revealed a significant cycle at 26 Myr and an only slightly less significant cycle at 30 Myr. Using less extensive data, Fischer and Arthur[3] had already suggested a 32-Myr periodicity in marine mass extinctions.

Which periodicity, 26 Myr or 30 Myr, should be preferred? Raup and Sepkoski listed all discernible mass extinction peaks that exceeded 2% extinctions on a family level. As they were well aware, however, there are a number of uncertainties in their selection procedure. First, 2% may be too small to be statistically meaningful; Raup[4] elsewhere suggested the use of 10%. Second, there are several minor fluctuations on the time curve of mass extinctions, some of which Raup and Sepkoski selected as true peaks and others they rejected as spurious peaks. Third, as the resolution in time is only one geological stage, other individual minor mass extinction episodes may exist at the substage level. In view of these uncertainties concerning identification and significance, we consider it best to follow Raup[4] and adopt a cutoff of 10% extinctions, while disregarding all the minor inflections on the curve. The large remaining peaks then refer exclusively to the major mass extinction episodes and can be assumed to be completely sampled. They are listed in Table 1 (where the dates have been slightly revised according to ref. 5). Nine dates appear in this table, in contrast to the 12 listed by Raup and Sepkoski.

Intervals of time between successive episodes of major mass extinctions lie in the range 17–53 Myr, with mean time interval 29 Myr. We regard the large (50%) dispersion as physically real, although some of it must be due to uncertainties of the dating. Reasons given below suggest that the dispersion is randomly generated. If, however, a true underlying mean periodicity does exist and no major mass extinction episodes are either missing or redundant, we can unambiguously assign a cycle number to each episode (Table 1). Non-parametric tests (like those in refs 1, 2) are then no longer appropriate. Regression of the episode date on the cycle number by the method of least squares provides an unbiased estimate of the best-fitting mean period, which is found to be 30 ± 1 Myr. If other recently proposed geological time scales are adopted[1], essentially the same mean period emerges. This invariance is not surprising because the central limit theorem ensures that the presence of even rather large random errors in the dates will not significantly affect either the mean time interval or the best-fitting least-squares period.

If the cycle number is left as a free parameter, the best-fitting mean period P derived from a suitable non-parametric method[2], in which the observed times are fitted to a formula of the type $t = t_0 + nP$, is 26 Myr, where t, t_0 and n are an observed time, the most recent epoch and an integer, respectively. This would agree with Raup and Sepkoski's[1] result. However, Raup and Sepkoski have emphasized the approximate nature of any period that can be derived from so few data points. We prefer, in fact, the assignment of the cycle numbers as given above and therefore the period of 30 Myr. There are additional reasons for our preference: first, other kinds of geological data (including 41 dated impact craters) show periods of 30–35 Myr, and, second,

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the larger variance produced with the longer period actually appears to have a natural physical basis, as will be discussed below.

A cyclicity of the specific length and rough regularity shown by the marine mass extinction data is difficult to reconcile with a purely terrestrial triggering mechanism[1,6]. There is also no known solar mechanism that could operate on this long a time scale[7]. A galactic mechanism therefore appears to be the most likely. A number of cycles ranging from 100 to 900 Myr (refs 8–13), are associated with the slow revolution of the Solar System in the plane of the Galaxy about the galactic centre. These cycles, however, are much too long to explain the 30-Myr spacing of the major extinction episodes.

Several authors[13–16] have pointed out that the Solar System also executes a nearly periodic motion perpendicular to the galactic plane (in the z direction). Innanen *et al.*[13] have calculated the Sun's orbit backward in time in a simple, but physically reasonable, model of the Galaxy, and have found the average period for one complete vertical oscillation to be ~67 Myr. They remarked (as had Hatfield and Camp[15]) that a period of this length is similar to the known lengths of the geological periods. The physically meaningful cycles, however, are the dynamical half-periods, $P_{1/2} \approx 33$ Myr (plane crossing to plane crossing). The calculated crossing times of Innanen *et al.* are given in Table 1.

For a slowly moving object like the Sun, the vertical oscillation is essentially a simple harmonic motion governed by the local galactic mass density ρ_0. Innanen *et al.* adopted $\rho_0 = 0.20\ M_\odot\ \mathrm{pc}^{-3}$, which agrees with recent values of $\rho_0 = 0.14$–$0.21\ M_\odot\ \mathrm{pc}^{-3}$ determined from dynamical studies of nearby stars[17–21]. By using the harmonic relation $P_{1/2}\rho_0^{1/2} = \text{constant}$, we estimate the possible error associated with $P_{1/2} = 33$ Myr as less than ±3 Myr.

The galactic time series in Table 1 can now be compared more rigorously with the terrestrial mass extinction time series. The correlation coefficient computed for the two time series in columns 2 and 3 of Table 1 is very high ($r = 0.996$). Student's t-test for matched pairs[22] (successive time intervals matched between columns 2 and 3) confirms that the mean time interval in the terrestrial series does not differ significantly from the mean time interval, or half-period, of galactovertical oscillation (the probability that $t = 0.91$ with 7 d.f. is $p = 0.40$). No mean phase difference between the two series is detectable, but some individual phase differences are large. Both the tight mean correlation and the significant individual phase differences suggest the following astrophysical model.

Passage of the Sun through the galactic disk involves the Solar System in varying amounts of diffuse interstellar material whose density falls off roughly exponentially above and below the galactic plane,

$$N(z) = N_0 \exp(-|z|/\beta) \tag{1}$$

But the Sun's total vertical trajectory is only ~70 pc (ref. 13), which is less than the vertical scale height $\beta \approx 120$ pc for ordinary interstellar gas and dust clouds[23] ($n = 10^1$–10^2 particles cm^{-3})[24] and less than $\beta \approx 100$ pc for the clouds ejected by supernova explosions[25,26]. Therefore, the Solar System has an almost constant probability of hitting one of these clouds. Because of this, no real periodicity between encounters with either ordinary or supernova-produced clouds could exist. Moreover, significant collisions with supernova ejecta would probably occur less frequently than once every 50 Myr (refs 27–30). Giant molecular clouds (with $n > 10^3$ particles cm^{-3}) are more closely concentrated towards the galactic plane ($\beta \approx 15$ pc assuming $\beta = 2^{-1/2}\langle z^2\rangle^{1/2}$)[31], but their encounters with the Sun are expected to occur less frequently than once every few hundred Myr (refs 6, 32, 33).

Unless the giant molecular clouds[6] or other very dense interstellar clouds[24] are much more common than presently thought, the most likely perturbing objects are intermediate-sized clouds. These have $n = 10^2$–10^3 particles cm^{-3}, radius $R = 3$–6 pc and mass $M = 10^3$–$10^4\ M_\odot$ (ref. 24). They seem to be adequately concentrated to the galactic plane, with $\beta \approx 44$ pc (ref. 31). They also appear to be more or less uniformly distributed along the galactic plane[34]; at least they do not show the strong concentration to spiral arms that is characteristic of the largest clouds[35].

Table 1 Dates (Myr BP) of terrestrial and galactic events

Geological age[1]	Mass extinctions[1]	Galactic plane crossings[13]	Difference	Cycle no.
Middle Miocene	11*	~0	+11	0
Late Eocene	37	31	+6	1
Maastrichtian	66	64	+2	2
Cenomanian	91	100	−9	3
Tithonian	144	135	+9	4
Bajocian	176	166	+10	5
Pliensbachian	193	197	−4	6
Norian	217	227	−10	7
Dzhulfian	245	259	−14	8

The mass extinctions listed here are the major events discussed in the text. Mass extinction dates have been revised after ref. 5. Columns 2 and 3 are not expected to agree in detail, for reasons given in the text.
* The magnitude of this episode is uncertain.

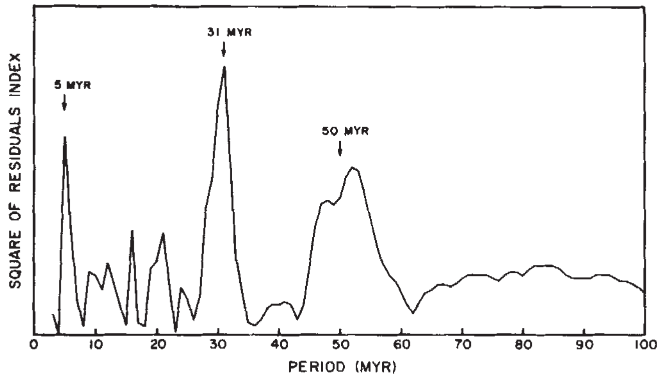

Fig. 1 Terrestrial impact craters: the square of the residuals index (defined in ref. 2) as a measure of the goodness of fit for trial periods that have been fitted to the observed age distribution of 41 craters over the interval $t = 1$–250 Myr (ref. 49).

To obtain a direct comparison with the vertical distribution of the clouds, the amount of time spent by the Sun at different intervals of height above or below the galactic plane is shown in Table 2; this has been computed by using an analytical integral of the galactovertical orbit equation[36]

$$t(z) = (P_{1/2}/\pi)\sin^{-1}(z/z_{\max}) \tag{2}$$

One-third of the Sun's time is spent at $|z| > 60$ pc. This almost guarantees an approximate cyclicity in the long-term rate of collisions with intermediate-sized and large-sized clouds, which will occur preferentially at lower $|z|$ distances, although not always in the galactic plane itself. Using the cloud statistics of Talbot and Newman[24], we estimate about 1 collision per solar passage through the galactic disk. If only tidal (near) encounters with clouds have to be considered, the rate will, of course, be higher.

The one-third of the Sun's time that is spent farthest from the galactic plane is expected to be associated with only 20% of all the collisions and tidal encounters with clouds whose $\beta = 44$ pc, but 33% if $\beta \gg 70$ pc. From the data in Table 1, we find that 11% (1 out of 9 as compared with the expected 2 out of 9) among the major terrestrial extinction episodes actually occur at this unfavoured time. Within the statistical uncertainty, the agreement with our model is good.

Although the Sun at present lies very close to the galactic plane (8 ± 12 pc north), it is passing through a locally poor region of gas and dust[23,27]. It is expected to move out of the region after ~3 Myr, at which time it will again become vulnerable to encounters with the intermediate-sized and large-sized interstellar clouds.

Table 2 Relative amounts of time spent by the Sun in successive intervals of galactic height

$\|z\|$ (pc)	z/z_{max}	$\Delta t/P_{1/2}$
0–7	0–0.1	0.06
7–14	0.1–0.2	0.06
14–21	0.2–0.3	0.07
21–28	0.3–0.4	0.07
28–35	0.4–0.5	0.07
35–42	0.5–0.6	0.08
42–49	0.6–0.7	0.08
49–56	0.7–0.8	0.10
56–63	0.8–0.9	0.12
63–70	0.9–1.0	0.29

Table 3 Summary of the mathematical solutions for terrestrial and galactic periodicities

Episodes	Ref.	Most recent epoch (Myr BP)	Cycle (Myr)
Terrestrial			
Mass extinctions (>10%)	1	10±7	30±1
Impacts	49	5±6*	31±1*
Galactic			
Galactic plane crossings	13	~0	33±3*

Terrestrial dates have been revised after ref. 5. Values for the most recent epoch are not significantly different from 0, in view of the size of the associated errors.
* Estimated error.

Two consequences of collisions and tidal encounters with such clouds that may have large ultimate biological impact have been suggested. First, if actual penetration of the cloud occurs, the cloud particle density of $n > 10^2$ cm^{-3} would probably shut off the solar wind at the Earth's distance, as Begelman and Rees[38] have shown. Such a cloud could then directly pollute the Earth's upper atmosphere with hydrogen gas, leading to a variety of possible climatic effects[39–41]. A larger cloud density of $n > 10^3$ cm^{-3} would also raise the Sun's luminosity significantly through gravitational accretion and so would directly affect insolation on the Earth[6,12]. To traverse a cloud of radius 5 pc at a relative speed of 20 km s^{-1} requires 0.5 Myr.

Second, and probably more importantly, even if an actual collision with a cloud does not occur, the cloud's huge mass would gravitationally perturb the Solar System's inner reservoir of comets[42] (as well as the surrounding Oort[43] comet cloud) and so focus a shower of comets on the innermost regions of the Solar System. According to equation (11) of Hills[42], comets having semi-major axes equal to the outer radius ($\sim 2\times 10^4$ AU) of the inner cometary reservoir will burst into the vicinity of the Earth's orbit if an interstellar cloud of mass 10^3–$10^4\ M_\odot$ approaches within 5–15 pc of the Sun. (Smaller interstellar clouds, because of the diffuseness of their mass, could effectively perturb only the Oort comet cloud and therefore would focus only a few comets to small perihelion distances, while significant encounters of the Sun with passing stars would occur only once every 500 Myr.) According to data from Hills, during the calculated 10 Myr lifetime of the expected comet shower[42], probably one large comet and several smaller comets would hit the Earth. Collision of a comet or a comet-derived asteroidal body with the Earth could have severe biological (and other geological) consequences[44–48].

Grieve[49] has recently compiled the ages of all dated Phanerozoic (younger than 600 Myr) impact craters. By applying the above mentioned non-parametric method of time-series analysis[2] to the data in his Table 1 and text and excluding ages given only as upper limits, we find strong signals at periods of 31, 5 and ~50 Myr, as shown in Fig. 1 for the time interval $t = 1$–250 Myr. These periods are significant at the 1% level, as we have determined by generating and analysing with the same method 5,000 random time series containing the same number of dates. The two periods of 5 and ~50 Myr are artefacts produced by the rounded numbers given for the ages of (mostly older) craters; 61% of the 41 crater ages ($t = 1$–250 Myr) are divisible by 5, while 22% are divisible by 50. The spectral peak around 31 Myr, however, is consistently high in all of our time-series tests, which include the ranges $t = 1$–250 Myr (41 craters), $t = 30$–250 Myr (29 craters), $t = 1$–600 Myr (62 craters) and $t = 250$–600 Myr (22 craters).

Some of the craters in the Grieve data set are likely to have been the result of impacts by asteroids of non-cometary origin. However, at present, it is not possible to distinguish between the two types of craters. In any case, non-cometary impacts should be randomly distributed in time and hence should only produce a non-periodic background contribution, like that from the occasional cometary impacts that do not originate from comet showers.

The distribution of the younger crater ages suggests that multiple impacts occurred around 15, 38, 65 and 100 Myr ago, as Seyfert and Sirkin[50] originally proposed. In view of the known dating uncertainties, the dates of these impact episodes are in reasonably good agreement with the dates of the mass extinction episodes of Table 1.

Comet or asteroid impacts have already been inferred from the discovery of geochemical anomalies occurring at the time of the late Cretaceous (66 Myr) extinctions[51,52], which included the disappearance of the dinosaurs, and at the time of the late Eocene (37 Myr) extinctions[53,54]. Several microtektite layers have also been discovered in the 10-Myr interval between 40 and 31 Myr ago[55]. Similar geochemical anomalies and microtektite layers should exist at other relevant boundaries.

If the geological consequences of episodic impacts go beyond immediate effects, as some authors have suggested[44–47], we predict that other kinds of terrestrial data should also show a mean periodicity of ~30 Myr. With similar techniques, a periodicity of 34 Myr has recently been found in the pattern of geomagnetic reversals[56]. Furthermore, we predict that when better extinction data for Palaeozoic times become available, the dominant cycle of major mass extinctions in these earlier times should be ~30 Myr. More speculatively, if one accepts our hypothesis that the basic pacemaker for biological extinctions is the Sun's vertical oscillation through the Galaxy, our line of reasoning can be reversed and we may refine the dynamical half-period of galactovertical motion near the galactic plane by using the terrestrial results summarized in Table 3. We then find $P_{1/2} = 30 \pm 3$ Myr (estimated uncertainty). This seems to support a large local dynamical mass density of $\rho_0 \approx 0.2\ M_\odot$ pc^{-3}. Whether this in turn implies the existence of 'missing matter' in the solar vicinity[19,20] is still uncertain. A last point worth considering for its philosophical implications is that the present mechanism should be operating at roughly the same driving frequency throughout the galactic disk.

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1. Raup, D. M. & Sepkoski, J. J. *Proc. natn. Acad. Sci. U.S.A.* **81**, 801–805 (1984).
2. Stothers, R. *Astr. Astrophys.* **77**, 121–127 (1979).
3. Fischer, A. G. & Arthur, M. A. *Soc. Econ. Paleont. Miner. Spec. Publ.* **25**, 19–50 (1977).
4. Raup, D. M. *Geol. Soc. Am. Spec. Pap.* **190**, 277–281 (1982).
5. Palmer, A. R. *Geology* **11**, 503–504 (1983).
6. McCrea, W. H. *Proc. R. Soc.* **A375**, 1–41 (1981).
7. Dilke, F. W. W. & Gough, D. O. *Nature* **240**, 262–294 (1972).
8. Hoyle, F. & Lyttleton, R. A. *Proc. Camb. phil. Soc.* **35**, 405–415 (1939).
9. Shapley, H. *Sky Telesc.* **9**, 36–37 (1949).
10. Steiner, J. & Grillmair, E. *Bull. geol. Soc. Am.* **84**, 1003–1018 (1973).
11. Williams, G. E. *Earth planet. Sci. Lett.* **26**, 361–369 (1975).
12. McCrea, W. H. *Nature* **255**, 607–609 (1975).
13. Innanen, K. A., Patrick, A. T. & Duley, W. W. *Astrophys. Space Sci.* **57**, 511–515 (1978).
14. Tamrazyan, G. P. *Izv. Acad. Nauk Azerb. SSR* **12**, 85–115 (1957.
15. Hatfield, C. B. & Camp, C. J. *Bull. geol. Soc. Am.* **81**, 911–914 (1970).
16. Meyerhoff, A. A. *Mem. Can. Soc. petrol. Geol.* **2**, 745–758 (1973).

17. Oort, J. H. in *Galactic Structure* (eds Blaauw, A. & Schmidt, M.) 455–511 (University of Chicago, 1965).
18. Eggen, O. J. *Publ. astr. Soc. Pacif.* **81**, 741–753 (1969).
19. Krisciunas, K. *Astr. J.* **82**, 195–197 (1977).
20. Hill, G., Hilditch, R. W. & Barnes, J. V. *Mon. Not. R. astr. Soc.* **186**, 813–830 (1979).
21. Rohlfs, K. & Kreitschmann, J. *Astrophys. Space Sci.* **79**, 289–319 (1981).
22. Klugh, H. E. *Statistics, the Essentials for Research*, Ch. 10 (Wiley, New York, 1970).
23. Knude, J. *Astr. Astrophys.* **126**, 89–93 (1983).
24. Talbot, R. J. Jr. & Newman, M. J. *Astrophys. J. Suppl.* **34**, 295–308 (1977).
25. Ilovaisky, S. A. & Lequeux, J. *Astr. Astrophys.* **18**, 169–185 (1972).
26. Clark, D. H. & Caswell, J. L. *Mon. Not. R. astr. Soc.* **174**, 267–305 (1976).
27. Terry, K. D. & Tucker, W. H. *Science* **159**, 421–423 (1968).
28. Ruderman, M. A. *Science* **184**, 1079–1081 (1974).
29. Whitten, R. C., Cuzzi, J., Borucki, W. J. & Wolfe, J. H. *Nature* **263**, 398–400 (1976).
30. Clark, D. H., McCrea, W. H. & Stephenson, F. R. *Nature* **265**, 318–319 (1977).
31. Stark, A. A. in *Kinematics, Dynamics and Structure of the Milky Way* (ed. Shuter, W. L. H.) 127–133 (Reidel, Dordrecht, 1983).
32. Clube, S. V. M. & Napier, W. M. *Q. Jl. R. astr. Soc.* **23**, 45–66 (1982).
33. van den Bergh, S. *J. R. astr. Soc. Can.* **76**, 303–308 (1982).
34. Sanders, D. B., Scoville, N. Z. & Solomon, P. M. Preprint, Univ. Massachusetts (1984).
35. Cohen, R. S., Cong, H., Dame, T. M. & Thaddeus, P. *Astrophys. J.* **239**, L53–56 (1980).
36. Chandrasekhar, S. *Principles of Stellar Dynamics*, 190 (University of Chicago, 1942).
37. Vidal-Madjar, A., Laurent, C., Bruston, P. & Audouze, J. *Astrophys. J.* **223**, 589–600 (1978).
38. Begelman, M. C. & Rees, M. J. *Nature* **261**, 298–299 (1976).
39. Talbot, R. J. Jr, Butler, D. M. & Newman, M. J. *Nature* **262**, 561–563 (1976).
40. Butler, D. M., Newman, M. J. & Talbot, R. J. Jr *Science* **201**, 522–525 (1978).
41. McKay, C. P. & Thomas, G. E. *Geophys. Res. Lett.* **5**, 215–218 (1978).
42. Hills, J. G. *Astr. J.* **86**, 1730–1740 (1981).
43. Oort, J. H. *Bull. astr. Inst. Neth.* **11**, 91–110 (1950).
44. Urey, H. C. *Nature* **242**, 32–33 (1973).
45. Napier, W. M. & Clube, S. V. M. *Nature* **282**, 455–459 (1979).
46. Clube, S. V. M. & Napier, W. M. *Earth planet. Sci. Lett.* **57**, 251–262 (1982).
47. Silver, L. T. & Schultz, P. H. (eds) *Geol. Soc. Am. Spec. Pap.* **190**, 1–528 (1982).
48. Pollack, J. B., Toon, O. B., Ackerman, T. P., McKay, C. P. & Turco, R. P. *Science* **219**, 287–289 (1983).
49. Grieve, R. A. F. *Geol. Soc. Am. Spec. Pap.* **190**, 25–37 (1982).
50. Seyfert, C. K. & Sirkin, L. A. *Earth History and Plate Tectonics*, 383–389 (Harper & Row, New York, 1979).
51. Alvarez, L. W., Alvarez, W., Asaro, F. & Michel, H. V. *Science* **208**, 1095–1105 (1980).
52. Hsü, K. J. *Nature* **285**, 201–203 (1980).
53. Ganapathy, R. *Science* **216**, 885–886 (1982).
54. Alvarez, W., Asaro, F., Michel, H. V. & Alvarez, L. W. *Science* **216**, 886–888 (1982).
55. Keller, G., D'Hondt, S. & Vallier, T. L. *Science* **221**, 150–152 (1983).
56. Negi, J. G. & Tiwari, R. K. *Geophys. Res. Lett.* **10**, 713–716 (1983).

Periodic mass extinctions and the Sun's oscillation about the galactic plane

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Raup and Sepkoski[1] have recently reported evidence for a 26-Myr periodicity in the occurrence of mass extinctions based on a study of marine fossils. The data baseline of 250 Myr suggests events of variable amplitude, with some of the strongest peaks associated with boundaries between major geological periods which have been defined by previous palaeontological studies. In a more limited quantitative study, Fischer and Arthur[2] earlier cited evidence for a 32-Myr period of major extinction events. Hatfield and Camp[3] were among the first to suggest that mass extinctions might be correlated with periodic galactic phenomena, noting intervals of 80–90 Myr between major mass extinctions with an exceptionally strong mass extinction every 225–275 Myr. Here we point out a possible correlation between the 26-Myr extinction period and the Sun's oscillation about the galactic plane.

Due to the disk-like mass distribution of the Galaxy, stars in the disk (including the Sun) experience a restoring force towards the galactic plane which gives rise to harmonic oscillation perpendicular to the galactic plane. Stellar velocity distributions have been used empirically to derive the force law in the galactic plane[4]. Oort calculated a period of the Sun's 'z-oscillation' on the order of 68 Myr and an amplitude of ~100 pc on either side of the midplane of the Galaxy[5,6]. More recent work by Bahcall[7] indicates a slightly stronger force law in the galactic plane than that derived by Oort, suggesting an oscillation period of ~62 Myr. Hatfield and Camp[3] cited earlier work of Trumpler and Weaver[8] which suggested a period of 80 Myr for the oscillation, close to one of the major mass extinction intervals. In addition, they attributed the strong mass extinctions at ~250-Myr intervals to the period of the Sun's revolution around the centre of the Galaxy.

In considering the Sun's harmonic oscillation about the galactic plane, it is important to recognize that the Sun crosses midplane twice in each period, and similarly that it reaches maximum distances from midplane twice each period. Thus any correlation relating to the Sun's position in this oscillation might well involve half the oscillation period, or ~31 Myr. The discrepancy of 5 Myr with the Raup and Sepkoski figure[1] may not be significant in view of the uncertainties associated with establishing each of the periods. In using the Harland time scale for their data set, Raup and Sepkoski recognized the difficulties in establishing an absolute time scale on the basis of a combination of chronostratigraphical sequences and radiometric dating. At the same time, the derivation of the force law in the galactic plane relies on assumptions involving isotropy of the stellar z-velocity distributions. Although isotropy may be indicated by z-velocity distributions of nearby catalogue stars within the local standard of rest (LSR), the LSR could itself possess a z-oscillation which, superposed on the solar oscillation, could yield an effective solar half-oscillation of <31 Myr. We suggest that present uncertainties would easily allow equal periods of ~30 Myr for the geological data as well as for the solar oscillation.

What circumstances could trigger the mass extinctions as a function of the Sun's galactic z-position? Passage of the Sun through dense dust clouds located at midplane could in principle provide a perturbing effect on the solar irradiation of Earth, thus initiating climatic changes which would affect the biosphere. However, there is no astronomical evidence for a widespread, flattened dust distribution of sufficient opacity to trigger such an effect with each solar midplane passage. Moreover, data suggest that the Sun is presently only ~8 pc north of the midplane of the Galaxy[9]. As the Sepkoski and Raup analysis indicates that we are presently about midway between mass extinction episodes (the two most recent episodes were ~11 Myr and 38 Myr in the past), this would suggest that the episodes are triggered as the Sun approaches its extreme positions away from the galactic plane. The exceptionally strong extinction event at 65 Myr (the Cretaceous–Tertiary boundary) could have resulted from the superposition of the impact of an asteroid on the longer time scale periodic extinction which was near maximum at the time. This would account for the fact that significant faunal extinctions in excess of those expected from the level of background extinction seem to have been well underway before the deposition of the iridium layer attributed to the impact[10,11].

What other agents of the galactic environment might serve to modulate evolution in the biosphere? Hatfield and Camp[3] suggested that geomagnetic field reversals might be triggered by variations in the galactic magnetic field as the Solar System moves through the galactic plane. At times of null magnetic field strength during the reversals, the increased cosmic ray flux at the Earth's surface could imperil the biosphere. To our knowledge, however, there is no evidence for a periodicity of ~30 Myr in geomagnetic field reversals. Moreover, the galactic magnetic field is six orders of magnitude weaker than the geomagnetic field, and in view of the fact that the magnetic flux associated with the solar wind at Earth is greater than the galactic magnetic flux, it is difficult to understand how the galactic field could perturb the geomagnetic field.

There are two components of the galactic environment which might be expected to undergo substantial changes from the point of view of a star oscillating through a distance comparable to the scale height distribution of interstellar matter. First, electromagnetic radiation in the 2 keV–1 eV range is strongly absorbed by interstellar material which in general obscures sources located more than 1 kpc from the Sun. If a source of radiation is located at midplane at a distance D from the Sun, and if the extinction law can be written

$$\kappa_\nu(z) = \kappa_\nu(0)\exp(-z/L) \tag{1}$$